

RESEARCH REPORT

The learning processes of two high-school biology students when reading primary literature

Gilat Brill, Hedda Falk and Anat Yarden, Department of Science Teaching, Weizmann Institute of Science, Rehovot 76100, Israel; e-mail: anat.yarden@weizmann.ac.il

Biology education, like education in any other discipline, strives to make students familiar with the knowledge, activities, and ways of thinking of the community of biologists. We produced a curriculum in developmental biology based on learning through primary literature, in an attempt to develop biological literacy among high-school students. Here we characterize the way in which two high-school biology students read a research article in developmental biology. Mere reading resulted in superficial comprehension. In contrast, when the students answered questions about the text, deeper comprehension evolved. The students could overcome reading-comprehension problems by applying well-established reading strategies, but encountered difficulties resulting from the classical structure of research articles. We hope that our characterization of the learning process of research articles by high-school students will enable the use of these complex texts in high-school biology classrooms.

Introduction

Considerable debate has focused on whether learning processes are the cognitive self-organization of knowledge or an enculturation into established practices (Cobb 1994). According to the first view, namely constructivism, individuals have their own ways of constructing knowledge, and learning is achieved through an active process of construction (Greeno et al. 1996). Curricula in science education should, therefore, encourage active learning, and allow opportunities for students to construct their own knowledge. According to the other view, namely situated learning, group interactions, social activities and even language play a fundamental role in the learning process. Learning is therefore a process of enculturation into the community of experts, until eventually, literacy in the domain is achieved (Brown et al. 1989). In this view, educators should design curricula that, for example, would 'bring the practice of knowing mathematics in school closer to what it means to know mathematics within the discipline' (Lampert 1990: 29). These two trends are not necessarily in contrast, since learning can be viewed as a combination of those processes (Cobb 1994). The question still remains as to how to combine these two views.

Biology education, like education in any other discipline, strives to make biology students familiar with the knowledge, activities, and ways of thinking of the community of biologists, and help them become biologically literate. The question of what scientific literacy is or what a literate person should know or be able to do

is controversial (Laugksch 2000). One of the many definitions of scientific literacy, which was published by the Program for International Students Assessment, is 'the capacity to use scientific knowledge to identify questions and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity' (Harlen et al. 2000: 2). Another definition states that a scientifically literate individual 'uses scientific knowledge and scientific ways of thinking for individual and social purposes' (American Association for the Advancement of Science 1990). A major component of scientific literacy is the ability to locate and comprehend scientific information, and to communicate scientific ideas and persuade others of their veracity (Holliday 1994). It is therefore acceptable to maintain that the reading and comprehension of scientific texts is an important component of scientific literacy, and should be an educational goal (Biological Sciences Curriculum Study 1993, Trowbridge and Bybee 1996, Uno and Bybee 1994).

The accumulated research on reading has revealed that learning from texts is a complex skill, which involves complex interactions between the reader's mind and the text, rather than a one-way flow of information from the writer to the reader (Holliday et al. 1994). Linking the content of the text with existing knowledge structures (Kintsch 1989), constructing meaning (Samuels 1983), and being able to represent knowledge in different ways, while maintaining motivation and interest (Asher 1980, Epstein 1970) are only a few examples of the complexity involved. Expert scientists perform these cognitive actions quite automatically when they read scientific texts, while novices may find it a difficult task (Alexander and Jetton 2000, Samuels 1983).

Scientists usually report their research work in research articles, also termed primary literature, which are published in professional journals. At the university/college level, courses that are accompanied by, or even based on, the reading of primary literature are quite common (Bandoni Muench 2000, Epstein 1970, Janick-Buckner 1997). In contrast, high-school students deal mostly with texts obtained from textbooks, popular research news from the media, and review articles from popular journals (Jarman and McClune 2002, Wade and Moje 2000, Wellington 1991). These types of texts contain descriptions of scientific research performed by scientists who are usually not the authors, and are therefore termed secondary literature. Although biology teachers tend to use secondary literature during instruction, it is not usually done systematically (Wade and Moje 2000), and biology lessons are usually not based on learning from texts.

Primary literature can have many benefits as a means of teaching a subject matter and developing scientific literacy. Research articles provide the academic background from which the research question emerged and describe experiments that preceded the present research work. If high-school students were able to read research articles, they could develop the following components of scientific literacy: acquaintance with the rationale of the research plan; exposure to research methods and their suitability to the research question; acquaintance with the language and structure of scientific communication; development of the ability to critically assert the goals and conclusions of scientific research; exposure to problems in a certain discipline and the ways scientists try to solve them, and acquaintance with the continuity of scientific research processes (Yarden et al. 2001). In addition, students may find reading research articles a novelty and a challenge (Epstein 1970), and may also identify with the quest of the researchers

reporting their work. Finally, since biology is one of the most dynamic research disciplines within the natural sciences, the gap between the accumulated knowledge in biology and the knowledge that is taught in schools is rapidly widening (Brill, Falk and Yarden 2003). The usage of primary literature in the high-school biology curriculum may help close this gap.

With this rationale in mind, we developed a curriculum based on primary literature in developmental biology for senior high-school biology majors in Israel (Yarden and Brill 2000). In addition to processing research articles so they suit the cognitive level of high-school students, the curriculum includes an introduction with the main principles in developmental biology and major research questions in the field (Yarden et al. 2001). The rationale governing the development of this curriculum was that learning through research articles can serve as a means of bringing the practice of knowing biology in school closer to what it means to know biology within the discipline, just as Lampert (1990) suggested for mathematics.

Here we report on our attempts to characterize the way two high-school biology students read a research article from the curriculum in developmental biology. Together with the reasons for miscomprehension, we describe the reading strategies the students used and the change that evolved in their understanding. In a way, their effort to understand the research article combined a constructivist way of learning with the beginning of a process of enculturation into the community of expert biologists reading primary literature.

Methodology

Learning from text (Samuels 1983), and, in particular, learning from research articles, is a complex process. Therefore, for the analysis of the learning process using research articles, we chose to use a qualitative approach, which would allow us to obtain rich and in-depth data as well as to analyze several variables (Guba and Lincoln 1998).

Students

Two 12th-grade biology students (Yael and Liat – pseudonyms) were videotaped in a laboratory setting while learning through a research article in developmental biology. Yael and Liat both study in the same biology class in an urban high school in Israel, situated in an upper middle class socio-economic neighborhood. They were chosen by their teacher because of their verbal abilities, over several other students who volunteered to perform the task.

Scientific backgrounds of Yael and Liat

According to information from their biology teacher, Yael and Liat are considered good students, but not with the highest achievements in their class. During the previous year, their class studied genetics as an advanced topic (according to the high-school biology syllabus in Israel, see later). During the year of the research, Yael and Liat's class was one of several classes used to test the new curriculum in developmental biology (Yarden and Brill 2000, and see later). Before conducting the research with Yael and Liat, their class had studied one of the four research articles from the curriculum and some relevant parts of the introduction to the

curriculum. In this research, Yael and Liat were asked to read another article from the four research articles in the curriculum.

The developmental biology curriculum

In Israel, at the end of the 10th grade, students choose to major in at least one scientific or non-scientific topic, which is evaluated in a national matriculation examination. The syllabus for the biology-major studies in Israel requires 450 hours of teaching (Israeli Ministry of Education 1991) and includes, in addition to basic topics, advanced topics that are aimed at reflecting the dynamics of biological research and discovery. It also includes the use of scientific papers by the students as part of their learning process (Yarden et al. 2001). The curriculum unit in the area of developmental biology (30 hours of teaching), which we developed as one of the advanced topics, has been previously described in detail (Yarden et al. 2001). Briefly, the program introduction describes principal stages in embryonic development and presents five key research questions in developmental biology. Each question is accompanied by a short discussion, which presents the rationale that led to posing the question.

The main part of the program contains four research papers in developmental biology obtained from professional refereed journals, focusing on four different research questions. Apart from the translation of the original papers to Hebrew, each paper was modified as follows: (1) essential information was added to the introduction of the article in order to help students understand the academic background of the research question; (2) the scientific methods used in the research and the discussion were simplified and adapted to the students' level; (3) results that did not relate directly to the research questions were omitted; and (4) a section about the contribution of the research to the understanding of processes occurring in humans, as well as in other organisms, was added to each paper.

Since we retained the common structure of research articles, as well as the authentic results and illustration, and since the modifications were only meant to simplify the text, but not to change it significantly, we referred to the modified versions of the research articles for high school students as 'primary literature'.

The task

The two students received a copy of an article from the curriculum, together with questions about the article. They were requested to read the article and answer in writing as many questions as time would permit. They were instructed to read the article together and discuss it, but to write down their written answers separately. Yael and Liat were also requested to speak aloud about the difficulties they encounter during the reading. One of the authors remained present in the room so they could ask for her advice if they needed it. Reading the article and answering the questions lasted an hour, followed by a half-an-hour semi-structured interview.

The research article

The research article that was handed to Yael and Liat was based on an article that described the possible mechanism responsible for the development of digits along the limbs of vertebrates (Riddle et al. 1993). This research combined classical and

molecular approaches in developmental biology. The article and some of the research methods were new to the students, and this was the first time they had read about them.

Discourse questions

The main rationale behind the questions that were handed out to the students was to create a kind of discourse between the students and the article, leading the students to build their own knowledge structure while reading the article. This is in contrast to a situation in which the teacher transfers the content of the article to the students.

The questions were variable, and referred to different sections of the article (abstract, introduction, methods, results and discussion). The first question was a reflective question on the abstract of the article. The reason for this was to start with a question that any student, with either low or high cognitive abilities, could answer. The aims of the following questions were: (1) to emphasize the difference between past experiments that are brought up in the introduction of the article, from which the research question emerged, and the experiments that were conducted in the currently reported research; (2) to help the students connect between the terms they use in class and the real research language; and (3) to clarify the differences between the experiments that were conducted in the reported research.

Data analysis

Microanalysis was applied to a transcript that was prepared from the videotape. The discourse between the students allowed one to understand the difficulties they encountered during the stage of initial reading. Each time one of the students stopped reading and consulted her peer was considered as revealing some kind of difficulty. Usually, most difficulties were explicit, and described overtly by the students themselves. This approach was also applicable for the reading comprehension strategies. Each difficulty the students encountered or strategy the student used were considered as a different category (see results for the different categories used). Since during this stage of the reading the students described overtly their difficulties and strategies, their uttered explanations were quoted. Some of the difficulties appeared in a few places in the transcript, but only one event was quoted.

In the stage of repeated reading, we used an *in situ* approach, which elicited some reflection on the students' way of thinking, by asking them questions during the video recording of the task. For example, after the students answered a given question, we asked them whether it was difficult for them to answer it and why. The answers the students wrote down separately served to triangulate the way we interpreted the videotape.

Results

Before Yael and Liat even looked at the questions, and although the questions and the article were handed to them together, they first read the article from beginning to end. We could therefore characterize two main stages in their reading process: the stage of initial reading, and the stage of repeated reading that took place as they tried to answer the questions.

Stage of initial reading

We analyzed the initial stage of reading the research article according to the possible reasons for the difficulties that Yael and Liat encountered, and the strategies they applied to overcome these difficulties.

Possible reasons for difficulties in reading. At this stage of reading the article for the first time, Yael and Liat read it separately. Each time one of them had some difficulty in understanding the text, she stopped and asked for her friend's help. We attempted to characterize the reasons for these difficulties:

1. *Unfamiliar scientific language.* When the text included unfamiliar terms or expressions. For example: 'What is the polarizing zone?' (Liat), 'These names drive me mad' (Liat), 'What does taxonomy mean?' (Yael).
2. *Three-dimensional perception of the embryo.* Since the article deals with certain parts of the embryo and the acquisition of their normal position during embryonic development, it is important to understand where these parts are situated during development in order to understand the text. For example: 'the polarizing zone is only in the caudal part, right?' (Yael), 'Where did they get a mirror image?' (Liat).
3. *Contradiction with prior knowledge.* Comprehension difficulties also appeared when the text apparently contradicted prior knowledge. For example, the text mentions a method that uses genetically engineered viruses. 'I didn't understand what kind of cells the virus makes contact with . . . because viruses, I remember that . . . when we learnt about it in 10th grade, they are specific . . . they bind specific receptors on specific cell types' (Yael).
4. *Text style.* On one occasion, Yael and Liat appeared to stop reading because the text was not coherent. In this particular place in the text, a conjunction was missing between two paragraphs, without which the paragraphs seemed unrelated. 'I didn't understand the connection between *hedgehog* and *Drosophila* [= fruit fly]' (Yael).

Reading strategies. During the initial reading of the article, Yael and Liat applied a few reading strategies that helped them comprehend the text:

1. *Connecting prior knowledge.* Yael and Liat made connections between the present article and another article that they had learnt together with the whole class. They also connected it to the knowledge they had acquired from the introduction of the curriculum, and to other subjects they had learnt that did not relate to the developmental biology curriculum. 'Right. All this is the methods of the . . . [other article we learnt on the] *Drosophila*' (Liat).

In an attempt to understand one of the suggested models in the discussion section of the article, Liat connected the text to her knowledge on the ratio between surface area and volume (a ratio often discussed in biology lessons at the high-school level): 'So, it is as if . . . so less cells . . . as the surface area becomes smaller then more and more cells are exposed to it [to the molecule]'.

2. *Using illustrations.* To clarify to herself and to Liat what she had read in the text, Yael (and to a lesser extent Liat) used the illustrations in the article.

Liat: 'Where did they get a mirror image?' Yael (answering Liat): 'Oh, look, see this illustration? It is supposed to be only this . . . [showing something in the illustration]'.

3. *Repeated reading.* A well-described strategy, for beginning readers as well, is to repeat the reading of the text that was not understood. Yael and Liat used this strategy as well: 'That's the way I understood it . . . wait, we can read it again.' (Liat, answering Yael's question), Yael: 'Wait, but what will they see? *Hedgehog* is present in the polarizing zone as well'. Liat (in response): 'It can be that . . . wait, we have to read it again' (and reads the text again).
4. *Making predictions.* For the novice reader, understanding a method that is described in the methods section of a research article usually involves understanding the experiment that was conducted using this specific method. This experiment is presented later on in the results section of the article. At a certain point in the methods section, Yael predicted the experiment that would use the method she was reading about, and also its possible results: 'And then, actually, here they produce *hedgehog* [a name of a gene], and also here they produce it, because of the virus. I think this is the case . . . and if it is so, then it is supposed to give us the same result here, that it is duplicated'. This prediction helped Yael better understand the method she was reading about.
5. *Using added explanations.* One of the ways to adapt the level of the research articles in the curriculum to the academic level of high-school students was to add explanations of terms that we thought would be unfamiliar in the margins of the text. Yael (and to a lesser extent Liat as well) made use of these explanations, usually in answer to Liat's questions.
6. *Ignoring technical term.* In one case, Liat declared that she did not understand the name of the gene the research deals with, and therefore she chose to ignore its meaning. Yael: 'They probably found it first in hedgehogs. That's why they named it like that'. Liat: 'I already stopped analyzing the names'.
7. *Asking the expert.* During the initial stage of the reading, the author who was present in the room was asked only once about a term that Yael and Liat did not understand, and was not explained in the text. 'Excuse me, what is taxonomy?' (Yael).

Other characteristics. Another important characteristic of this initial reading stage was that Yael and Liat had the feeling that they understood the article. They freely expressed this feeling after silently reading different parts of the text: 'I think I understood the abstract' (Yael), 'OK. I understood this' (Liat).

From time to time, they would point out what they thought they understood, unaware of the fact that they had understood the text in the wrong way. For example, after Liat finished reading the whole article for the first time she stated: 'These are the same conclusions of the [article on] *Drosophila* [referring to the article they learnt with the whole class]. It is just another experiment'.

Their feeling of understanding was even stronger when they read the results section. During their cooperative reading of the methods section, Yael and Liat predicted the main experiment of the research quite well. When they reached the results section and found out that their prediction was right, they felt they

understood the text very well. Therefore, they read the results section very quickly, only briefly studying the main illustration showing the main results, and almost completely ignoring the table showing the quantitative results.

Stage of repeated reading

Yael and Liat finished their first reading of the article with a general feeling that they had understood the text and at this stage they started to answer the questions. For this purpose they had to re-read the relevant parts of the article.

The first question dealt with the abstract and asked them to reflect on the level of understanding of this part of the article. Yael claimed she understood the abstract very well, although not perfectly. In contrast, Liat was able to explain and point out her difficulties. Liat stated: 'I understood the terms [of the abstract], but I didn't quite understand how they are related to each other'.

We could find several characteristics of the stage of repeated reading.

Declaring miscomprehension. While trying to answer the questions, Yael and Liat found more and more parts of the text that they had not understood. 'What does it mean [that the strain of the chick] was not resistant?' (Liat), 'This part. It isn't clear what they are doing. [The part of] the checking with the virus' (Yael).

Asking the expert. This stage was characterized by the students often turning to the author present in the room, and included asking for clarification, trying to solve difficulties, and so on. 'Excuse me, what does it mean "if it wouldn't have been resistant [to the virus]"? What do they mean?' (Liat).

Miscomprehension. The discourse between Yael and Liat while they were trying to answer the questions revealed some misunderstandings of the text, which were created during their first reading of the article, but were not revealed then. For example, neither fully understood the rationale behind the method used in the research. 'So, they did one experiment that they did the RNA and saw the color, and another experiment that they transplanted cells . . .' (Yael). In fact, the second experiment did not involve any RNA.

Acknowledging the complexity of the text. While answering the questions, Yael and Liat discovered that their answers were not identical. This led them to acknowledge the complexity of the text. In addition, they realized that the research question of each experiment is not explicitly mentioned in the text. This is in contrast to what they are used to in biology laboratory at school, where they are always requested to phrase the research question and their hypothesis. Liat: 'What we wrote down was a little different, so this means that . . . the text is not straightforward'. Yael: 'It doesn't tell you here anywhere what they are looking for . . . so . . . the research question is a question that we figured out from the text'.

Mixing up the experiments described in the article. On one occasion that Yael addressed the author who had remained in the room, it becomes evident that she conceived two experiments in the results section as one experiment, or at least similar experiments that made use of the same method (which is not the case). Yael: 'When they did the cell transplantation, were these cells also with stained RNA?'.

Yael and Liat also confused a past experiment that was brought up in the introduction of the article with the main experiment shown in the article, which had been based on this past experiment. This became apparent due to one of the questions, which required describing the past experiment in terms of the research question, variables, results and conclusions. In their answer to this question, both students described a mixture of the two experiments (the past experiment and the main experiment in the article).

Scientific literacy. The article proposes a model to explain the mechanism of activity of a certain molecule during embryonic development. One of the questions involved explaining why the model is only a suggestion, and not a conclusion drawn from the research. Liat's answer was: 'The model is only a suggestion because it isn't possible to conclude firm conclusions only according to one experiment'. This answer may indicate a basic misconception; that is, that many repetitions of the same experiment must be conducted in order to prove a hypothesis. This is in contrast to what is accepted in the scientific community: that conducting different experiments to prove the same hypothesis strengthens the scientific claim.

Reaching a deeper understanding. During the effort to answer the questions, Yael and Liat began a process of deep understanding of the text. This understanding was achieved either by addressing the expert present nearby, or by peer-learning. For example, at some point of a discussion with the expert, Liat realized what the meaning of the results of the main experiment in the article could be: 'Now, just a second. This means that actually the development of the digits is not so dependent on the polarizing zone, meaning that . . . it is dependent on the gene itself'.

In this process of deep understanding, Yael and Liat could explain how they had previously misunderstood the text. When they were asked where their mistake was, Liat claimed: 'It isn't clear at all which cells they are taking, that it is done actually in two . . . in two stages'. Yael is also aware of the process she is going through: 'This part with the viruses is really not clear. Every time [I read it again] I understand something that I didn't understand before'.

Reflection

After they had read the article and answered the questions, we interviewed Liat and Yael. In this interview they reflected on the process of their reading of the research article. The following issues were evident from the talk:

1. Yael and Liat were aware of the difference between reading the article for the first time and reading it again. Yael: 'After you understand it and you read it again, then you understand. But after you read it for the first time you don't understand what they did there'. Yael also points out that at first reading there are 'holes' that make it difficult 'to understand the connection'.
2. They were also aware of the fact that when they explained the difficulties to each other the first time they read the article, they hadn't always understood it right. Liat: 'there are things which we could understand ourselves, like . . . what we talked about, but it wasn't always right'.
3. Liat was also aware of the fact that she could not separate between the different experiments in the article. Liat: 'I, for example . . . I didn't have

a clear cut between the first and the second experiment. I mean, it got all mixed up. I took it as one experiment instead of two'.

4. Difficulties that emerged from the scientific report method:
 - a. Yael claimed that separating the description of the results (the results section) from their meaning (the discussion section) makes it difficult to understand. Yael: 'The fact that the results and the explanation of the results are not together is quite confusing. Because, I mean . . . you read the results and then you say: OK, what does it mean? . . . and then when you read the discussion you have to go back to the results again because you don't remember what was there'.
 - b. The description of the experiment does not include explanations of the conduct of the experiment. Liat: 'They say only the aim and the results. I mean . . . they didn't really explain what they did . . . and . . . what their intention was in every experiment'.
5. Yael and Liat pointed out several times that the questions were important for better understanding the article. Yael: 'Did you notice? It was only when we started working on the question that we realized what we didn't understand'.

Interestingly, when we asked Yael and Liat how would they recommend a friend to read the article, they said it was better to read the introduction and the discussion sections first, and only then the other sections. Yael: 'If you read the abstract and the introduction – they give you general background . . . The methods and the results are not so clear, so if you read the discussion and then you read them – you understand what they did'.

Discussion

We characterized two main stages in the learning process of the two students through the research article: initial reading in which the readers believed they fully understand the article, and a second stage in which the readers of the article realized their miscomprehensions and attempted to understand the misunderstood details.

Superficial reading

The coherence of the research article, apart from one place that lacked a proper conjunction, resulted in the students' general feeling that they understood the article after reading it for the first time. This is in contrast to the second stage of reading, in which the students understood that there was a deeper level to the text and that their understanding had been more superficial upon their first reading of the article. This phenomenon has been described in research showing that coherent text stimulates superficial understanding and is best used with low-background-knowledge students (McNamara et al. 1996). In contrast, non-coherent texts (e.g. lacking proper conjunctions or hierarchy) stimulate thinking and deeper understanding among high-background-knowledge students (McNamara et al. 1996). Indeed, it was postulated that confusion is an important aspect of learning and that clarity of instruction (in our case, the coherence of the text) may lead to superficial levels of understanding (Norman 1978).

The role of questions about the text

Questions about the text are known to influence the reader's learning process: questions posed before reading tend to restrict the reader's attention to question-relevant text (Burton et al. 1986). In addition, questions that are inserted in the text have a forward-transfer effect (Sagerman and Mayer 1987): they tend to guide the reader's attention to the main issues of the questions also during further reading.

The students who participated in the research described here read the article for the first time without looking at the questions they had to answer. Therefore, the approach they chose in order to confront the task enabled us to observe the naïve way in which they constructed knowledge from the research article, without the influence of any directing questions. Indeed, one important problem was that these students could not distinguish between various experiments presented in the article. Instead of a fragmented view of the article, which might be expected from novice readers (see later), they constructed their own meaning from the text, connecting pieces of information in the article (an experiment from the introduction section and an experiment from the results section) that should have been understood separately. In addition, they did not read the results section of the article thoroughly and therefore missed the main point of the research.

The questions about the text that were provided to the students changed the meaning they gave to the text. Since it was inevitable that the intrinsic logic of the question would contrast with the meaning they had constructed from the text, the students had to rethink the text, and thus deeper thinking was stimulated. Rethinking resulted in a change in the way one of the students (Liat) understood the main point of the article. After reading the article for the first time she claimed: 'These are the same conclusions of the article on *Drosophila* [another research article from the curriculum they had learnt in the class]. It is just another experiment'. In contrast, after trying to answer a question on the article that dealt with the different experiments of the study she changed her mind: 'Wait a minute, this means the development of the digits is dependent on the gene itself . . . This is the conclusion of this whole experiment! We have learnt something now!'.

Expert–novice differences

One interesting aspect of the research conducted on the processes of reading primary literature by high-school students is the difference between expert reading and novice reading. Two of the main components of expert reading are schemas and automation (Alexander and Jetton 2000, Kintsch 1989, Sweller and Chandler 1994). Preformed schemas are cognitive structures consisting of general outlines that can be found in similar situations/processes/objects and give meaning to the information in the text, even though it had never been read (Kintsch 1989, Sweller and Chandler 1994). Automation occurs after constructing schemas, when the expert unconsciously applies the appropriate schema to the situation (Alexander and Jetton 2000, Sweller and Chandler 1994). A novice reader does not have such schemas, or does not use them in an automated way (Alexander and Jetton 2000).

An example of such differences between expert and novice research article readers can be seen in the way the two students understood the abstract of the

research article. One of them (Liat) described difficulties in understanding the abstract, claiming that she could not put the details together and create a coherent understanding of the text. In contrast with this fragmented cognitive structure, expert readers can apply preformed schemas to construct the main outline of the research that is about to be read from the abstract, although they have never read about it before. Therefore, for expert readers, the abstract serves as a form of advance organizer (Ausubel 1963). In contrast, Liat, who is a novice reader, could not construct meaning from the abstract, and might have read other parts of the research article (like the introduction or the methods) as an advance organizer, mainly due to the resemblance between the experiments described there and in the results. Indeed, the two students regarded the information in the introduction as information about the research itself, and could not distinguish between the experiments described there and in the results section.

The role of different sections in the research article

One would expect that sectioning research articles into distinct parts – which summarize the article (abstract), give the relevant scientific background (introduction), report the scientific methods (methods) and the results of the research (results), and finally discuss their meaning and raise new research questions (discussion) – should facilitate better comprehension of the information provided by the research. Without any doubt, the expert reader has a firm concept of what the different parts of the article should entail. As already mentioned, the abstract serves as an advance organizer for the expert, and preformed schemas are automatically applied to understand the text. These abilities, and the orderly way in which the scientific research is reported, enable expert readers to read, comprehend and even criticize the research (Alexander and Jetton 2000, Yarden et al. 2001).

The two students, being novice readers, might have found this orderly way of reporting to be an obstacle, due to the complexity of the text as well as the unfamiliar structure of the research article. In an attempt to characterize the reasons for difficulties in learning new material, Sweller and Chandler (1994) argue that there is limited capacity in our working memory, in contrast to the extensive capacity in our long-term memory. According to Sweller and Chandler (1994), when learning new material involves the simultaneous acquisition of several elements of information that have no meaning when learnt separately, the cognitive load on our short-term memory results in learning difficulties. Sweller and Chandler (1994) termed the extent of interaction between these elements the complexity of the new material. In this view, the different sections of research articles can be considered informational elements that have no meaning when read separately and therefore contribute to the cognitive load of the two novice readers. This may be, for example, because reading the methods section for the first time had no meaning for the students without understanding the rationale of the research and the consequent results.

This interpretation of how Yael and Liat as novice readers might have dealt with research articles can be viewed in the way the two students comprehended the research article. They read the research article in a chronological manner. Reading the methods section before the results section had no meaning for them. To overcome this problem – namely, in order to give meaning to the methods section – the students started thinking in the methods section about the experiments and

their predicted results. Subsequently, when they reached the results section, they felt that they already knew the experiments and had even predicted their results. Therefore, they did not read the most important section of the article (the results section) thoroughly and could not distinguish between the experiments, or relate the right method to each experiment.

The same problem might have occurred when they read the results section. Without the interpretation, the results had no meaning for the two students. One of the students (Yael) indicated the cognitive load she encountered when reading the article: 'the fact that the results and the explanation of the results are not together is quite confusing. Because, I mean . . . you read the results and then you say: OK, what does it mean? . . . and then when you read the discussion you have to go back to the results again because you don't remember what was there'. She then recommended that a student reading the article for the first time read the introduction section and the discussion and only then the methods and results. Indeed, Sweller and Chandler (1994) suggested that one reason for cognitive overload may be the physical separation between related pieces of information in the material to be learnt.

The two students could not distinguish between various experiments that appeared in the article. A possible reason for this difficulty is the fact that the method used in the different experiments may be identical, although the research question is different. The novice readers of research articles that we followed (Yael and Liat, and other students in several lessons that we observed) might need guidance in distinguishing between apparently identical experiments.

A developmental model

Novice readers gradually become more literate by reading research articles, and after many experiences of reading primary literature acquire the characteristics of expert readers. Alexander and Jetton (2000) suggested a developmental model of learning from text, which involves three levels of academic development. Readers in the first level are at the stage of acclimation. They are unfamiliar with the domain, and therefore have little relevant prior knowledge. Readers at this stage try to build basic knowledge for themselves and therefore need a well-explained and coherent text. Their motivation to read is usually extrinsic and they therefore lack real interest in the text.

At the second level of reading, readers become competent. They have more background knowledge, and find more interest in the text. In addition, competent readers can read text with coherence gaps and begin to think and perform like members of the domain community.

Expert readers have the highest level of learning from text. Background knowledge is structured and multidimensional, there is strong interest in the text and an intrinsic motive for deep understanding. Processing and comprehension of the text are automatic and facilitate criticism.

This model of the development of an expert reader is in accordance with other views on phases of learning (Shuell 1990). According to these models, learning involves three main phases. The initial phase involves the acquisition of pieces of information and the usage of pre-existing schemas to interpret the newly encountered information. The intermediate stage involves the active formation of new schemas, and the final stage involves the automation of these schemas.

The way in which the two students read the research article for the first time indicated, at times, that they were in the acclimation (or initial) stage, and at times that they were at the competence (or intermediate) stage. Their relevant prior knowledge was small, but they seemed to be able to overcome coherence gaps and reach a superficial understanding with no outside help. In order to learn from research articles, readers must become competent and form new schemas, and in a way the questions about the text lead the students towards this stage of reading. In addition, to facilitate the transition from the initial phases of learning to the intermediate phases, our curriculum includes a well-structured and coherent introduction to the domain of embryonic development (Yarden et al. 2001).

Implications for instruction

The findings of this research have several instructional implications for using research articles in the high-school biology classroom. We previously observed that biology teachers tend to ask students, as part of their homework, to read the articles themselves. Reading of text is an important stage in learning through research articles, which allows the students to construct their own knowledge initially, by themselves. Nevertheless, since the first reading of coherent texts may result in superficial learning, mere reading is not enough to stimulate deeper understanding.

As already mentioned, the process of reading is viewed as an interaction between the reader's mind and the text (Holliday et al. 1994). In an attempt to stimulate this kind of interaction, we developed a teaching strategy in which reading the article is accompanied by student-generated questions about the text, as well as their anticipation of the next steps of the research (Yarden et al. 2001). A similar approach was previously developed for beginning readers to improve their comprehension of texts (Palinscar and Brown 1984). We suggest using this model as a way to overcome the cognitive load created by the different sections of the article, which cannot be understood separately.

Another possibility may be to recommend that novice readers read the results section before the methods section or, if possible, to read each experiment described in the results section and then the relevant method. Reading about the methods after the results might give the right context to each method and to each experiment, and enhance the comprehension process of the research article. Nevertheless, this learning approach might impair some of the major benefits of learning through research articles; for example, the ability to predict the experiments and the research plan, or the ability to criticize the research.

In addition to the approaches mentioned, metacognitive approaches in the process of learning through research articles might be used. For example, students can evaluate their level of understanding of the abstract, as Yael and Liat did. Another example is to ask them to reflect on the way they read the article and what should be changed the next time they read it.

One important implication of the research is the contribution of the questions and tasks to Yael and Liat's deeper comprehension of the text. Therefore, it is important that teachers who teach through research articles incorporate a variety of tasks and questions, with specific goals such as knowledge organization, reading comprehension, prediction, criticism, and so on, in the ongoing of the lesson, as well as in team tasks.

Conclusions

Learning biology through research articles is a complex process, which involves interaction between the reader and the text. The two high-school students that were followed in this research attempting to read research articles have applied some previously acquired well-established reading-comprehension strategies. Nevertheless, they encountered difficulties in comprehending research articles, probably due to the lack of schemas and automation that expert readers possess and activate during their reading of the articles. The classical structure of a research article probably increased the cognitive load and made it difficult to understand each of its sections separately. However, learning from research articles can be a tool to familiarize high-school biology students with the knowledge, activities, and ways of thinking of the community of biologists, and help them become literate biologists. Alexander and Jetton (2000) claim that 'regrettably, few students experience the sensation of processing text as domain experts'. We hope the suggested approach of using primary literature as part of the high-school biology program, as well as our characterization of the learning process of two high-school students reading research articles, will enable the development of the required means to use such complex texts in additional high-school biology classrooms.

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